AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2014JC010470

Key Points:

- Southern Ocean eddy kinetic energy has increased in recent decades
- EKE trends can be primarily ascribed to stronger winds
- ACC transport has slightly declined over this period despite increasing winds

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Citation:
Hogg, A. McC., M. P. Meredith, D. P. Chambers, E. P. Abrahamsen, C. W. Hughes, and A. K. Morrison (2015), Recent trends in the Southern Ocean eddy field, *J. Geophys. Res. Oceans*, *120*, doi:10.1002/2014JC010470.

Received 23 SEP 2014
Accepted 16 DEC 2014
Accepted article online 23 DEC 2014

Recent trends in the Southern Ocean eddy field

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Abstract Eddies in the Southern Ocean act to moderate the response of the Antarctic Circumpolar Current (ACC) to changes in forcing. An updated analysis of the Southern Ocean satellite altimetry record indicates an increase in eddy kinetic energy (EKE) in recent decades, contemporaneous with a probable decrease in ACC transport. The EKE trend is largest in the Pacific (14.9 ± 4.1 cm^2 s^{-2} per decade) and Indian (18.3 ± 5.1 cm^2 s^{-2} per decade) sectors of the Southern Ocean. We test the hypothesis that variations in wind stress can account for the observed EKE trends using perturbation experiments conducted with idealized high-resolution ocean models. The decadal increase in EKE is most likely due to continuing increases in the wind stress over the Southern Ocean, albeit with considerable interannual variability superposed. ACC transport correlates well with wind stress on these interannual time scales, but is weakly affected by wind forcing at longer periods. The increasing intensity of the Southern Ocean eddy field has implications for overturning circulation, carbon cycling, and climate.

1. Introduction

The Southern Ocean is one of the most eddy-rich areas of the global ocean, containing regions with the largest eddy amplitudes [*Fu et al.*, 2010] and receiving in excess of 60% of the global ocean wind work [*Hughes and Wilson*, 2008]. Eddies in the Southern Ocean play a key role in modulating the ocean circulation response to forcing. For example, in numerical simulations of the Southern Ocean, an increase in transient eddy activity caused by enhanced wind stress appears to offset increases in the large-scale zonal transport of the Antarctic Circumpolar Current (ACC) [*Hallberg and Gnanadesikan*, 2006; *Meredith and Hogg*, 2006, hereafter *MH06*]. Following convention, we refer to the theoretical limit in which ACC transport is independent of wind as "eddy saturation" [*Hallberg and Gnanadesikan*, 2001]. Transient eddies may also help to partially counteract wind-driven increases in the upper cell of the circumpolar meridional overturning circulation (MOC) [*Hallberg and Gnanadesikan*, 2006; *Viebahn and Eden*, 2010; *Meredith et al.*, 2012], a process that has become known as "eddy compensation," although it is likely that the modulation of standing meanders is also important in this process [*Zika et al.*, 2013a; *Thompson and Naveira Garabato*, 2014].

The eddy field in the Southern Ocean has a complicated relationship with surface forcing. For example, *MH06* showed that the Southern Ocean eddy field (as measured by area-averaged eddy kinetic energy, EKE, inferred from satellite altimetry) responds to interannual variations in circumpolar wind stress (or Southern Annular Mode, SAM, index) with a lag of 2–3 years. This lag is consistent with eddy-resolving numerical model simulations of the Southern Ocean (*MH06*) and a similar lag is found to apply regionally [*Morrow et al.*, 2010].

Of primary interest here is understanding how the major Southern Ocean current systems—specifically, the Antarctic Circumpolar Current (ACC) and the circumpolar MOC—respond to changes in surface forcing. These current systems control interbasin exchange of nutrients, heat, and salt, as well as playing a major role in the carbon cycle and heat content of the deep ocean. However, developing a full understanding has been hampered because observational constraints on the evolution of ACC and MOC strength are limited. A recent review of Drake Passage baroclinic transport [*Meredith et al.*, 2011] indicates a mean ACC transport of

137 ± 7 Sv inferred from over 15 repeat hydrography sections since 1995, with no significant trend. Overturning circulation cannot be measured directly, but is inferred using inverse methods [e.g., *Lumpkin and Speer*, 2007], and there is little direct information on its changes in recent years despite its acceleration having been invoked as a leading cause of a proposed saturation of the Southern Ocean sink for atmospheric carbon dioxide [see *Le Quere et al*., 2007]. Therefore, many studies are limited to analysis of model results. In recent years, computational advances have allowed progressively more sophisticated model analysis of the range of responses of the Southern Ocean to changing wind stress. A series of eddy-permitting ocean models with idealized domains and forcing (but with a realistic ocean overturning circulation) have been demonstrated to be close to the eddy saturated limit [e.g., *Jones et al*., 2011; *Shakespeare and Hogg*, 2012]. In these models, the response of ACC transport to changes in wind stress is both weaker and slower than the response of the eddy field, and is a strong function of surface buoyancy forcing on centennial time scales, implying that the slow mode of response is produced by reorganization of the global stratification [*Jones et al*., 2011]. In some circumstances, an eddy saturated limit is possible even with primitive equation models [*Hogg*, 2010; *Munday et al*., 2013].

Global eddy-permitting ocean models have also supported the notion of a multiyear lag between wind stress anomalies and the eddy response [*Screen et al*., 2009], as well as there being a less sensitive ACC transport [*Spence et al*., 2010] and weaker overturning response to changes in forcing [*Farneti et al*., 2010] compared with those seen in coarse resolution models. On subannual time scales, the net ACC transport is more sensitive to variations in wind stress near the Antarctic margin than along the ACC path [*Mazloff*, 2012; *Zika et al*., 2013b] consistent with a barotropic response linked to nearly closed f/H contours close to the southern edge of the circumpolar belt [*Hughes et al*., 1999; *Kusahara and Ohshima*, 2009]. However, global models are computationally expensive to fully equilibrate, and residual trends in the evolution of stratification can complicate interpretation of Southern Ocean dynamics on comparable time scales [*Treguier et al*., 2010].

Model results have thus provoked discussion regarding the future evolution of the ACC, as well as the overturning circulation in the Southern Ocean. While the processes that generate eddies (wind generation of available potential energy, followed by baroclinic instability) are well known, the temporal response of these eddy-permitting models is essentially uncalibrated. Thus, it is necessary to consider the extent to which observations may help to constrain model projections. The most reliable observation of the Southern Ocean eddy response is the EKE record from satellite altimetry. In addition, variability in ACC transport may now be estimated using altimetry, albeit with caveats concerning the magnitude of changes on different time scales [*Hughes et al*., 2014]. On the other hand, the magnitude (or even the sign) of surface buoyancy forcing, and the response of the overturning structure in this region to changes in forcing, are essentially unconstrained.

In this paper, we update measurements of Southern Ocean EKE, compare them with a recent quantification of ACC transport, and examine relationships with surface forcing (section 2). These results are compared with scenarios from an idealized primitive equation model in section 3, constructed to test the extent to which changes can be attributed to wind stress. Our goal is to use the results from these lines of evidence to improve understanding of possible future trajectories of the ACC.

2. Data Sets and Processing

2.1. Southern Ocean Winds

The Southern Annular Mode (SAM) is the dominant mode of extratropical climate variability in the Southern Hemisphere. Figure 1a shows the annual running mean SAM index (black line), calculated per *Marshall* [2003], with positive values of the SAM indicating poleward intensification of the Southern Hemisphere westerlies. A long-term trend (1972 to present) is apparent (dashed line), which is distinct from interannual variability. However, the trend during the satellite altimetry era (1993 to present) is weaker than previous decades, reflecting the sensitivity to end points of a short record, combined with an anomalously high SAM index in 1993. Previous modeling studies [e.g., *MH06*; *Screen et al*., 2009] have indicated that the Southern Ocean eddy field applies an effective dynamical filter on variations in wind stress over time scales shorter than 3–4 years. Accordingly, the 4 year running mean SAM index is also displayed (red line), and captures the largest multiyear SAM anomalies, whilst otherwise being consistent with the long-term trend (Figure 1a).

Wind stress averaged over oceanic regions between 45°S and 65°S calculated from the ERA interim reanalysis [*Dee et al.*, 2011] (Figure 1b, black line) correlates well with the annually averaged SAM (correlation 0.88). Wind stress increases from 1990 onward at a rate consistent with the long-term trend (not shown) albeit masked by strong levels of interannual variability. We also show how the ERA-interim wind stress has varied within each ocean basin (Figure 1c). For this, we divide the Southern Ocean up into the three sectors similar to those used by *MH06* (Indian Ocean: 40°E–150°E, 57°S–44°S; Pacific Ocean: 150°E–288°E, 62°S–48°S; and Atlantic Ocean: 325°E–10°E, 56°S–46°S). The regional analysis indicates that the long-term trend in Southern Ocean wind stress is dominated by changes in the Pacific sector.

2.2. Southern Ocean Eddy Kinetic Energy

Transient eddy kinetic energy is computed as

$$\mathrm{EKE}=0.5\ \left(u^2+v^2\right) \tag{1}$$

where u is the zonal geostrophic current anomaly and v is the meridional geostrophic current anomaly from the temporal mean. The geostrophic current components can be estimated directly from high-resolution multimission altimetry products [e.g., *Ducet et al.*, 2000] and this has become the common data source to use for computing EKE [e.g., *MH06*]. Although this is convenient data to use, there is a possibility of signal attenuation due to the mapping functions used. For this reason, we have also computed the geostrophic velocity using the older crossover method [*Parke et al.*, 1987].

The computation of the geostrophic current anomalies directly from crossover data uses less smoothing of the sea surface height anomaly (SSHA) data. In the Southern Ocean, the crossover density of the TOPEX/Poseidon, Jason-1, and Jason-2 should sample the eddy field sufficiently. To compute SSHA gradients at the crossover points in order to calculate the geostrophic current anomalies, some smoothing is required; here we use the method of *Bretherton et al.* [1976] to optimally interpolate and smooth the along-track SSHA data to a regular 7 km spacing. The covariance function is modeled as a Gaussian with a roll-off of 98 km and random noise of 2 cm, which was determined from the autocovariance of all SSHA data from 1993 to 2012 between 40°S and 65°S. Gradients were computed at each crossover point for the ascending and descending directions using center differences, and the zonal and meridional geostrophic components were computed following *Parke et al.* [1987]. EKE was computed at each crossover point, and then averaged over the three sectors used for averaging wind stress in Figure 1c.

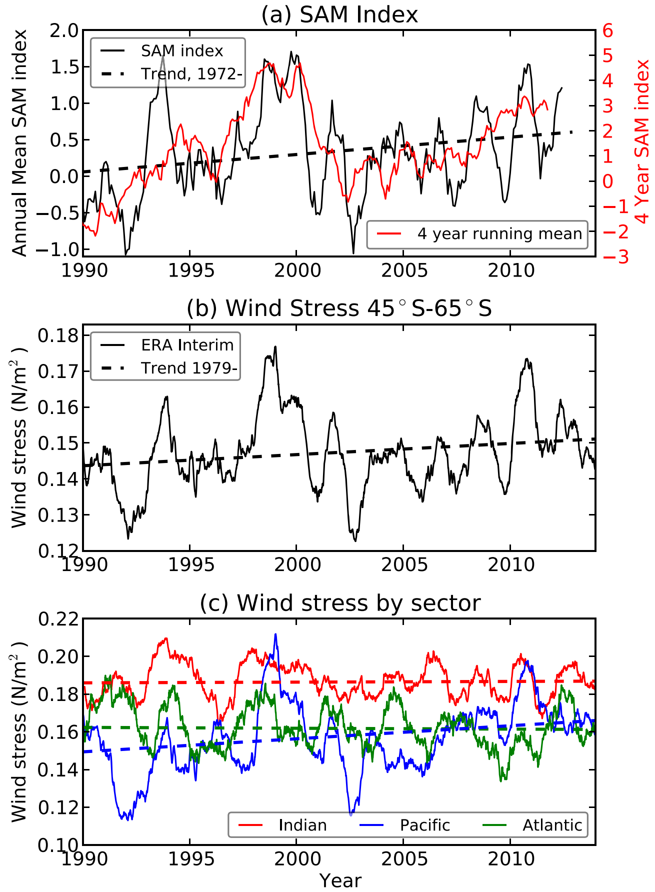

Figure 1. (a) Southern Annular Mode time series as per *Marshall* [2003] and *Fu et al.* [2010]. Annual running mean (black) and linear trend (dashed) from 1972 to present; 4 year running mean (red). (b) Wind stress averaged over the region 45°S–65°S, showing ERA interim (black) and long-term trend (thick dashed). (c) Wind stress integrated over three sectors of the Southern Ocean, with the long-term trend (dashed).

We tested whether the sampling of the crossovers could

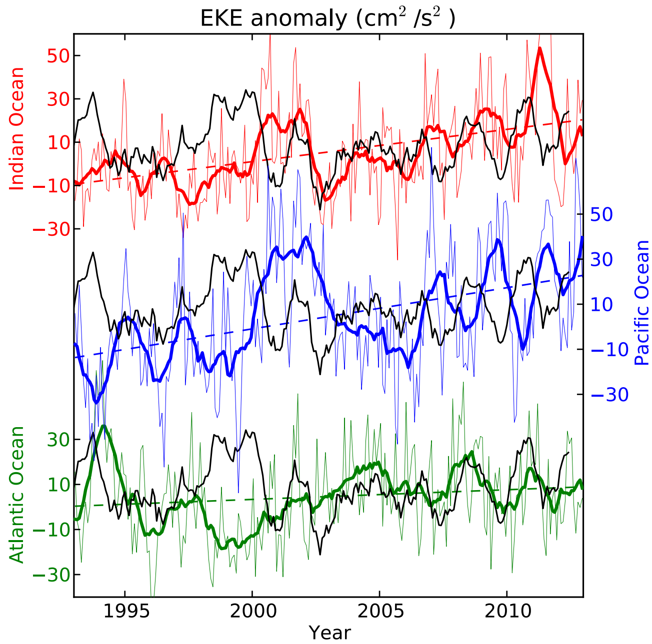

Figure 2. Eddy kinetic energy anomaly from crossover analysis for three Southern Ocean sectors: Indian Ocean (red), Pacific Ocean (blue), and Atlantic Ocean (green). Thin colored lines show raw data, solid lines show running annual means, while the dashed line shows the satellite altimetry era trend. The thin black lines show the rescaled 1 year running mean SAM index.

distort the calculation using the AVISO gridded products. The difference in 1 year EKE computed from the full grids and the same data set subsamples only at crossover points, averaged over each sector ranged from 2.3 to 3.6 cm^2 s^{-2} (one standard deviation), which amounts to 2% of the variance of the EKE computed using the crossover method, and so is considered insignificant.

Although the EKE anomalies computed from the crossovers and gridded data are highly correlated in each sector (with values ranging from 0.7 to 0.8 for 1 year averages), crossover EKE has significantly higher variability and mean values. There is very nearly a linear scaling between the two, suggesting the grids are attenuating approximately constant proportions of the signal. The values of the parameter needed to scale the gridded EKE to match crossover EKE are 1.6 (Atlantic sector), 1.7 (Indian sector), and 1.9 (Pacific sector).

We show the time series of EKE from the crossover analysis averaged over each of the three sectors since 1993 (Figure 2), since there is no evidence of bias due to sampling and there is apparent attenuation using grids. The results are consistent with *MH06*: peaks in the 1 year running mean SAM index (black lines) are lag-correlated with peaks in EKE in the Pacific and Indian Ocean sectors. With a 3 year lag (SAM leading EKE), the peak correlation for the Pacific is 0.50 ($p < 0.05$) while for the Indian it is 0.32 ($p < 0.1$), but the latter part of the record suggests that shorter lags ($\sim$1 year) are more plausible for individual events. There is no significant correlation between the SAM and Atlantic Ocean EKE, nor is the EKE in the Atlantic correlated with the Indian or Pacific sectors. There are differences in EKE between the three sectors, which is attributed by *Morrow et al*. [2010] to other climate modes of variability, such as the El Niño Southern Oscillation.

Figure 2 also shows a new and interesting result: a robust increase in EKE over the last two decades in the Pacific and Indian sectors at a rate of 14.9 $\pm$ 4.1 cm^2 s^{-2} per decade and 18.3 $\pm$ 5.1 cm^2 s^{-2} per decade, respectively, for the crossover EKE (uncertainty 90% confidence level). The trend in the Atlantic sector is smaller and only barely significant at the 90% confidence level: 4.0 $\pm$ 3.7 cm^2 s^{-2} per decade. When converted to percent relative to the mean EKE from 1993 to 2001, the trends are consistent using either crossovers or gridded data: 6.0 $\pm$ 1.6% per decade for the Indian Ocean and 6.4 $\pm$ 1.8% for the Pacific Ocean.

MH06 did not find a significant trend for EKE from 1993 to 2004, due mainly to the large natural variability toward the end of the record in 2000–2002, and because they used the attenuated EKE from the gridded data. Using the crossover EKE would have resulted in a significant trend in the Pacific sector over that time period. However, it is now a robust feature of the 20 year record, explaining >70% of the variance in the EKE computed from crossovers.

2.3. ACC Transport

It is now also possible to estimate ACC transport variability since 1993 using a method proposed by *Hughes et al*. [2014]. We calculate circumpolar sea level using AVISO gridded sea level data over the Antarctic continental shelf and slope, as defined in *Hughes et al*. [2014]. A bias (relative to other time series) and a seasonal cycle were removed from the time series at each point as part of the averaging process, in order to reduce

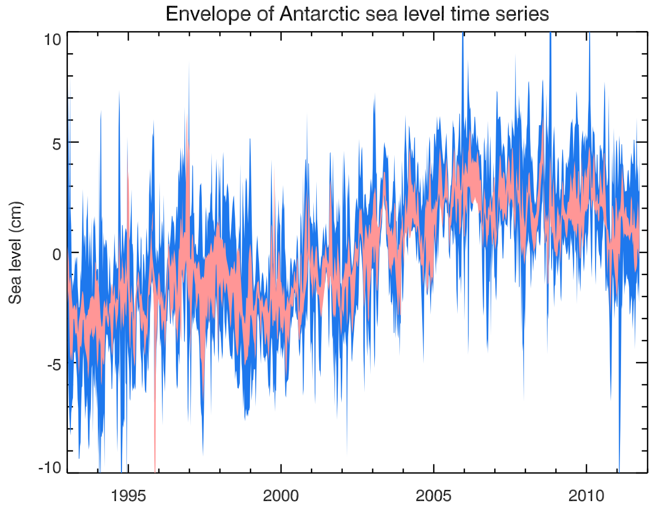

Figure 3. Antarctic sea level time series. The blue band represents the envelope of 12 time series from different longitude bands (0°E–30°E, 30°E–60°E, etc.), while pink shows the envelope of 5 time series averaged over all longitudes but binned by depth (0–1 km, 1–2 km, etc.). Annual and semiannual cycles have been removed.

artifacts due to the incomplete sampling in regions of seasonal sea ice cover. Figure 3 shows the robustness of the resulting sea level record to different choices of geographical regions. The time series we use averages over all depths and longitudes.

To calculate the ACC transport from the sea level record using the method developed by *Hughes et al*. [2014], we assume that sea level reflects transport at periods of approximately 5 years and shorter, with a conversion factor of −3.69 Sv/cm. At 10 years period, the factor is about 2.5 times smaller and may be smaller still at longer periods again; we have therefore adopted a "long period" factor of −1.11 Sv/cm (see *Hughes et al*. [2014], for full details). Thus, from the raw sea level record, h, we extract a long period curve, h_f, by fitting sine and cosine curves of periods 10, 20, and 40 years. We then estimate transport as

$$T = -3.69(h - h_f) - 1.11 h_f.$$

This transport estimate is plotted as the magenta curve in Figure 4. While the amplitudes of the scaling factors and their frequency dependence should be considered preliminary, their signs and the sense of their scaling with frequency are robust (see *Hughes et al*. [2014], for full details). An assumption is made that the changes are dominated by ocean dynamics, rather than gravitational changes which may dominate on even longer time scales.

The ACC transport since 1993 computed using this method does not support the notion of a wind-induced increase in the ACC over the last two decades; instead there are some indications of a weak decline. Superposed on this are significant interannual fluctuations correlated with the annual running mean SAM index (correlation of 0.65, $p < 0.05$, at zero lag after subtracting periods 10 years and longer). The clear relationship between wind and transport at zero lag indicates that, on periods of $<$10 years, the variability of the ACC is strongly dependent on wind stress forcing, as per *Meredith et al*. [2004], but at decadal time scales there is no evidence that wind stress influences ACC transport.

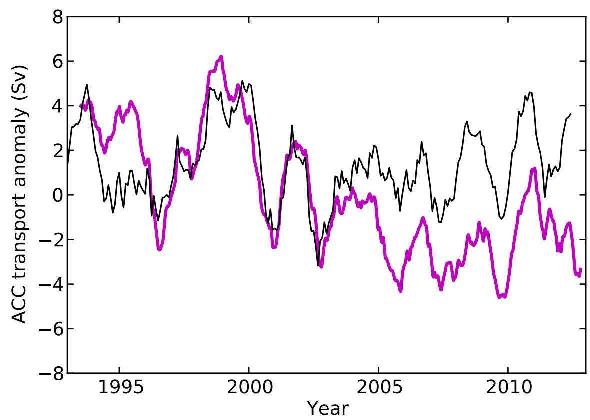

Figure 4. ACC transport estimated from circum-Antarctic sea level is shown by the magenta line. The thin black lines show the rescaled 1 year running mean SAM index.

The long period transport decline is associated with a rise in circumpolar sea level which is attributable to the increased addition of meltwater from the Antarctic continent [*Rye et al*., 2014]. The decrease in salinity, and an accompanying circulation-induced temperature increase, leads to accumulation of a band of more buoyant water on the continental slope and shelf, and hence a sea level rise. Because this rise is density related, as opposed to the barotropic sea

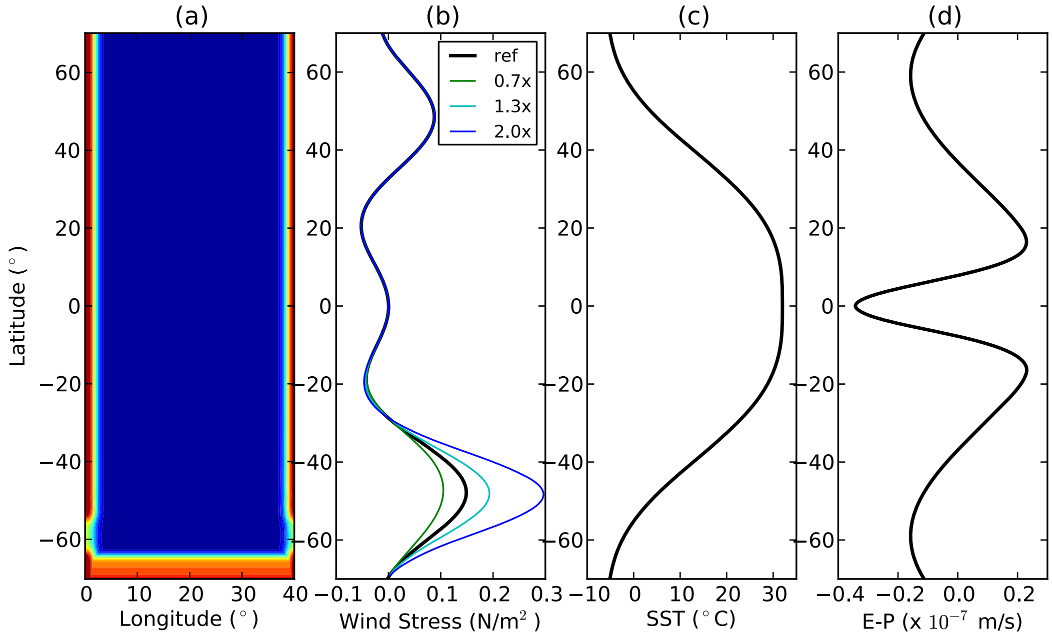

Figure 5. Model configuration. (a) Model bathymetry; (b) wind stress forcing for the four experiments; (c) sea surface temperature relaxation profile; and (d) prescribed freshwater forcing.

level changes associated with shorter period wind-driven variability, a larger sea level rise is required for the same change in circumpolar transport. This is consistent with the mechanisms delineated in *Hughes et al.* [2014], the change from barotropic to density-related sea level change being responsible for the changed conversion factor we adopt for periods of 10 years and longer.

3. Dynamical Investigations With High-Resolution Models

As seen above, the SAM index, and associated Southern Ocean wind stress, has a positive trend over the last 40 years. These trends have persisted over the last two decades, although strong interannual variability and sensitivity to endpoints makes those wind stress trends difficult to discern in some subsets of the data. Simultaneously, we have identified a robust trend in Southern Ocean transient EKE over the last 20 years, while ACC transport has not increased over this time (with a hint of a weak decline). We propose that the eddy saturation hypothesis may account for the long-term trend in EKE. This hypothesis would predict a linear response of EKE to wind stress on decadal time scales, and may explain the long-term EKE trend without significant increases in ACC transport. We test the viability of this hypothesis with numerical model simulations driven by a combination of prescribed wind stress and surface buoyancy fluxes.

3.1. Model Description

Modeling the ACC on long time scales for our purposes requires us to include (at a minimum) permitted eddies, as well as interactions between the ocean stratification and global overturning circulation. To make such simulations computationally feasible, we elect to reduce the complexity of our model domain [following *Jones et al.*, 2011; *Wolfe and Cessi*, 2011; *Shakespeare and Hogg*, 2012; *Munday et al.*, 2013] with simple bathymetry, using MITgcm [*Marshall et al.*, 1997a, 1997b] at both eddy-permitting (0.25°) and eddy-resolving (0.1°) horizontal resolution, with 36 vertical levels and a linear equation of state. The model domain has a simple bathymetry, spanning 40° in longitude and running from 70°S to 70°N (see Figure 5a). There is a reconnecting channel and sill mimicking Drake Passage in the southern part of the sector. Wind stress forcing (Figure 5b) and freshwater fluxes (Figure 5d) are prescribed and zonally symmetric, while thermal forcing occurs via relaxation to the sea surface temperature profile shown in Figure 5c, with a time scale of 20 days. (*Zhai and Munday* [2014] show a weak dependence of EKE and its sensitivity to wind stress upon this restoring time scale.)

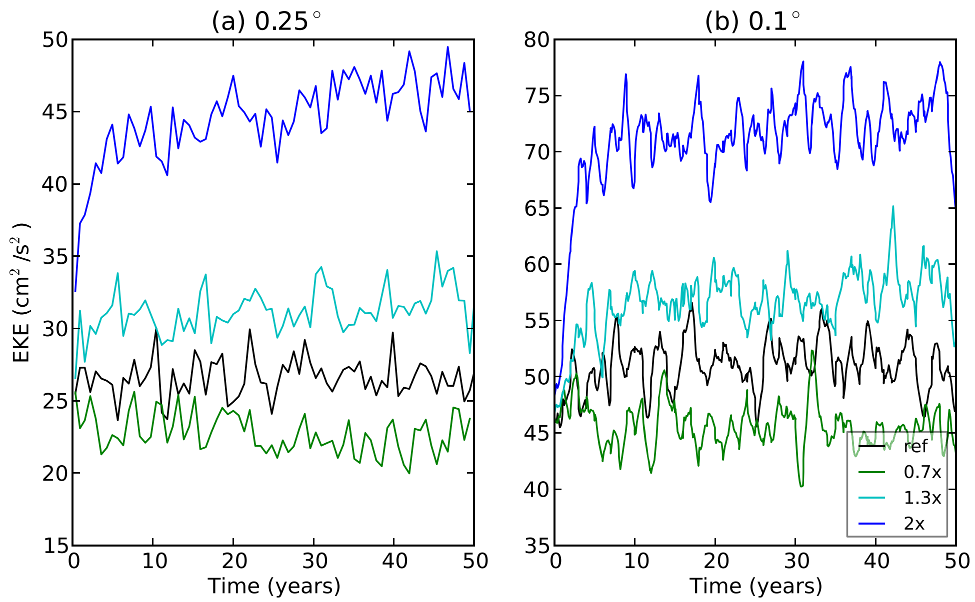

Figure 6. Modeled eddy kinetic energy response to increasing wind for the (a) eddy-permitting and (b) eddy-resolving simulations.

This modeling strategy is designed to enable explicit control over the model forcing to test the above hypotheses, while also allowing the model to reach equilibrium in a manner that captures the essential elements of the ocean circulation, within computational constraints. The model is equilibrated for 3000 model years at eddy-permitting resolution, before perturbing the forcing and running for another 50 years. The forcing perturbations include changes in Southern Ocean wind stress magnitude and wind stress position. In the present manuscript, we show only changes to the magnitude of wind stress; wind stress position tends to have only a weak effect on Southern Ocean zonal transport or EKE in this model. (Further information on the model configuration is detailed in A. Morrison et al. ("Possible link between recent decadal Southern Ocean surface cooling and a slowdown of the Antarctic Bottom Water circulation" submitted to *Journal of Climate*, 2014)). The wind stress magnitude (Figure 5b) is altered in the southern part of the domain only, with scaling factors of 0.7, 1.3, and 2.0. The change is maximum at 50°S, tapering off by 30°S and 70°S.

The strategy in these numerical experiments is to apply an instantaneous, stepwise change to the forcing field and to examine the transient response. This forcing differs from the observed changes, which include interannual variability and long-term trends; however, a stepwise change inherently includes a full spectrum of forcing frequencies and allows for better separation of the system's response on different time scales. Thus, variable forcing can be convolved with the impulse response function to predict the system's response to observed changes.

Each perturbation is applied individually from the same initial state allowing a direct comparison of the transient response. In addition to the eddy-permitting experiments, we repeat a number of experiments at higher resolution. Here the reference case is initiated from the equilibrated 0.25° case, and integrated for a further 125 years before the wind stress magnitude perturbations are applied. Our contention is that more emphasis should be placed on results which are independent of resolution, and stress that this experimental procedure is aiming to understand the dynamical response to change rather than being an attempt to accurately predict the magnitude of either the mean circulation or its sensitivity.

3.2. Results

Figure 6 shows the depth-averaged EKE response of the modeled Southern Ocean to instantaneous changes in surface wind stress for the 0.25° and 0.1° models. The eddy fields at the two resolutions differ markedly, due to improved resolution of the mesoscale at 0.1°, and lower lateral viscosity. The eddy-resolving simulations contain approximately double the average EKE (comparing the black lines in Figure 6). However, the response to changes in wind stress magnitude is less dependent on resolution. Both

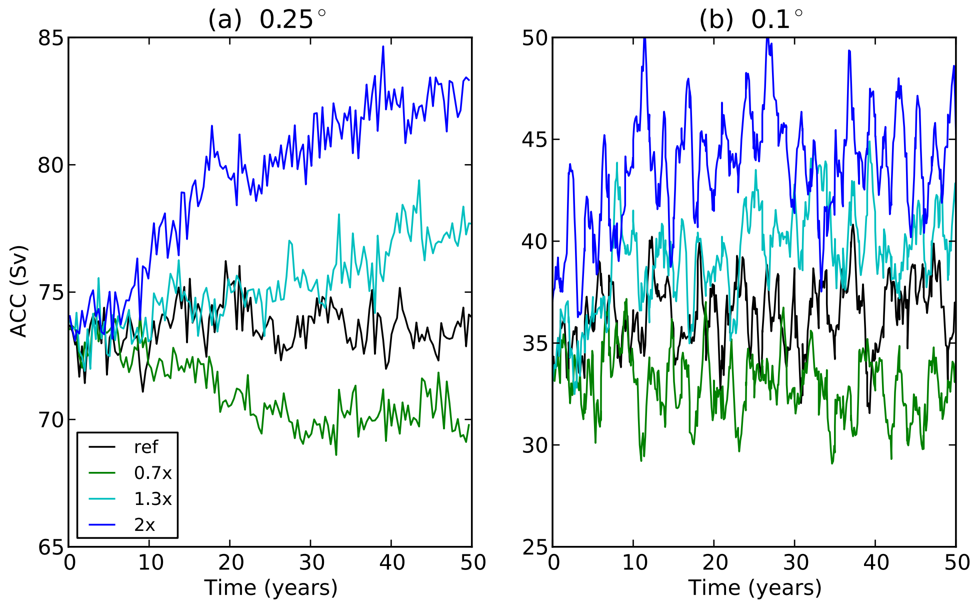

Figure 7. Modeled ACC transport response to increasing wind stress for the (a) eddy-permitting and (b) eddy-resolving simulations.

resolutions yield a rapid (within years) and near-linear response to the stepwise change in wind stress (Figure 6). The EKE response stabilizes to approximately 80% of its final value within 2–3 years, but a weak residual tendency over the remainder of the time series continues throughout the 50 year simulation.

The ACC transport response to model forcing (Figure 7) makes an interesting contrast to the EKE response. There is a smaller and more gradual response of ACC transport to the magnitude of wind stress (Figure 7). Under a 30% increase in wind stress forcing, the ACC transport change is not distinguishable until 25 years, although large variability in the eddy-resolving case makes it more difficult to discern trends. Thus, it appears that this model is close to the eddy saturated limit in the short term [*Hogg and Blundell*, 2006], but that perturbations to the ACC strength are achieved on long time scales through reorganization of the stratification [*Allison et al*., 2010; *Jones et al*., 2011]. Note that the wind stress is zero at the southern boundary in all experiments, so the fast barotropic response to wind stress close to the continent is suppressed; we are focusing here on the response to changing winds in the open ocean. Model investigations using the same framework but with imposed changes in buoyancy forcing (not shown) did not provide coherent, credible explanations for the observed pattern of change in EKE and ACC transport.

3.3. Time Scale of EKE Response

The modeled EKE appears to have two time scales of response to wind stress changes. The interannual response noted above occurs rapidly, within a couple of years, but there is an additional slow response with a multidecadal time scale. We evaluate the relative effects of these two time scales by normalizing the modeled EKE response by the magnitude of the perturbation in Figure 8a. We find that the resulting time series is well described by the equation

$$R(t) = 0.4\left(1-e^{-\frac{t}{2}}\right) + 0.2\left(1-e^{-\frac{t}{15}}\right)$$

shown by the heavy dashed line in Figure 8a, with uncertainty of the order of 40% (thin dashed lines). This estimate indicates that the rapid (2 year) response is twice the magnitude of the slow (15 year) response. We follow *Marshall et al*. [2014] in convolving this response with the time rate of change of the SAM index,

$$EKE(t) = \int_0^t R\left(t-t'\right)\frac{\partial(SAM)}{\partial t}\left(t'\right)dt'$$

to produce a scale estimate of EKE (black line in Figure 8b). This estimate is compared with the area-weighted average EKE from the three lines shown in Figure 2. While the correlation between these two lines

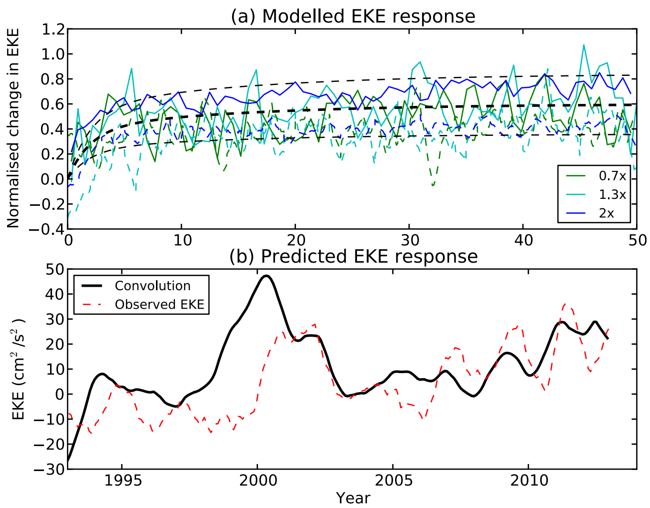

Figure 8. (a) Normalized model EKE response to a unit perturbation for both 0.25° (solid lines) and 0.1° (dashed) simulations, with the idealized response shown in dashed black lines. (b) Predicted EKE response to SAM (black) compared with circumpolar estimate of EKE.

is not exact, this approach supports the notion that the decadal trend in EKE primarily reflects the strength of ocean winds via the eddy field. By placing an effective interannual filter on wind stress, EKE may respond more conspicuously to decadal changes in wind stress than would otherwise be the case.

4. Discussion and Conclusions

Circulation in the Southern Ocean is driven by a combination of wind stress and surface buoyancy forcing, both of which display variability on a range of time scales. The data presented here indicate that decadal trends in the SAM index and wind stress over the last decade have been partly masked by large levels of interannual variability, but that there is evidence supporting an increase in Southern Ocean wind forcing since the early 1990s.

Transient EKE in the Indian and Pacific sectors of the Southern Ocean exhibits interannual variability over the satellite era. Consistent with previous studies [e.g., *MH06*; *Screen et al*., 2009], we find that interannual variability in EKE is well correlated with regional wind stress, with a 1–3 year lag. This result is also consistent with model simulations which show a rapid response of EKE to wind stress changes. Thus, both models and observations support the notion that transient EKE is primarily controlled by local wind stress on time scales $<$5 years.

In addition, we find an intriguing decadal-scale increase in EKE since 1992 in the Indian and Pacific sectors. EKE levels in 2013 are similar to the previous record-length maximum in 2002–2003 (which occurred after an anomalously strong SAM event at the end of the 1990s). Numerical simulations are used to evaluate the hypothesis that wind stress changes are responsible for observed increases in transient EKE. The direct correspondence between wind stress and EKE in all simulations is consistent with this hypothesis. Thus, while the processes at work in this model (energy input from wind stress decaying to baroclinic eddies) are known, the modeling results provide quantitative evidence that the observed changes in EKE can be attributed primarily to trends in wind stress (Figure 8).

We compute transient EKE using altimeter crossovers, giving values that are 1.6–1.9 times higher than that computed from gridded altimetry. Both methods find significant trends and nearly identical relative changes, of about 6.4 $\pm$ 1.8% increase in EKE per decade. Results from the crossover method imply that there may be a systematic underestimation of EKE when calculated from the gridded product. Although EKE is inherently only a relative measure, this underestimation could have significant effects on (for example) overestimation of the ocean power input due to wind stress forcing [*Hughes and Wilson*, 2008; *Scott and Xu*, 2009].

Estimated time series of ACC transport allow insight into the link between circumpolar flow and EKE. At time scales of $<$10 years, we see interannual variability that is strongly correlated with the SAM index—this appears to be a fast response to wind stress consistent with the results of *Meredith et al*. [2004] and *Zika et al*. [2013b]. However, over the full time series we see no evidence of an increase in ACC transport connected with EKE. On the contrary, there is evidence of a decrease, associated with rising circum-Antarctic sea level. Our ensemble of model simulations show that on long time scales ACC transport may increase with wind stress via reorganization of the stratification, but this process takes time to generate a discernible change in transport. However, these simulations do not include near coastal wind stress that are important in determining the more rapid response [*Zika et al*., 2013b]. The observed increase in EKE, without increasing ACC transport, is consistent with a response to a 30% increase in wind stress. The observed small decrease in ACC transport, however, argues for control of transport on decadal time scales by changing heat and/or freshwater fluxes [*Gent et al*., 2001; *Shakespeare and Hogg*, 2012]. This is consistent with the attribution of this signal by *Rye et al*. [2014] to the increased freshwater flux due to accelerated melting of Antarctic glacial ice.

Determining changes in ACC transport and associated transient eddies are important in understanding the Southern Ocean and its range of potential responses to climate changes. The ACC acts to integrate a wide range of ocean processes, thus understanding the temporal variability of the ACC will help us to calibrate and assess global ocean models, and enable increased reliance on these model projections. Currently, we are hampered by limited observations of the ACC and surface forcing, and the lack of a complete model that encapsulates all the important processes. These results indicate that future ACC transport and the Southern Ocean eddy field may be influenced by changes in wind stress, and motivate the need for reliable, sustained estimates of ACC transport, its variability and forcing.

In summary, we find a decadal increase in EKE in the Southern Ocean since the early 1990s, contemporaneous with a potential small decrease in ACC transport. There is evidence supporting the hypothesis that the EKE trend has been caused by the decadal trend in the SAM and the winds overlying the Southern. The EKE trend has significant implications for the efficacy of the Southern Ocean sink for carbon and heat, with global climatic implications.

Acknowledgments
We thank Gareth Marshall for providing the observed SAM data for this paper (see http://www.nerc-bas.ac.uk/public/icd/gjma/sam.html). The altimeter products were produced by Ssalto/*Duacs* and distributed by *AVISO*, with support from *CNES* (http://www.aviso.oceanobs.com/duacs/). Andy Thompson, Stephanie Downes, and two anonymous reviewers provided constructive criticism of the first draft of this manuscript. A.M.H. was supported by an Australian Research Council Future Fellowship (FT120100842). M.M. and E.P.A. were supported by NERC funding via the BAS Polar Oceans strategic research programme. D.P.C. was supported by NASA grant NNX13AG98G for the Ocean Surface Topography Science Team. C.W.H. was supported by NERC National Capability funding via NOC. A.K.M. was supported by the Carbon Mitigation Initiative, sponsored by BP. This research was undertaken on the NCI National Facility in Canberra, Australia, which is supported by the Australian Commonwealth Government.

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